

## EVIDENCE OF BASIN-AND-RANGE EXTENSIONAL TECTONICS IN THE SIERRA NEVADA: THE DURRWOOD MEADOWS SWARM, TULARE COUNTY, CALIFORNIA (1983-1984)

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### ABSTRACT

An extensive earthquake swarm occurred at Durrwood Meadows in the southern Sierra Nevada of eastern California during late 1983 and 1984. It was located within a 100-km-long linear belt of seismicity that cuts through the southern Sierra Nevada along a north-southward strike. This seismic belt has been characterized by swarms and was one of the most seismically active features in southern California during 1984. The Durrwood Meadows swarm itself was characterized by a complex spatial distribution and a simple pattern of focal mechanisms. At the beginning of the swarm, the earthquakes were located along a northwestward trend; later, periods of high seismicity were distributed along a northeastward trend forming a Y-shaped structure, and along other, northward and northwestward trends. In spite of this spatial complexity, the focal mechanisms of the 35  $M_L \geq 3.0$  earthquakes within the swarm are all similar to each other, with almost pure normal faulting along a north-southward strike. The strikes of the nodal planes in the focal mechanisms and the spatial distribution of epicenters form an en-echelon pattern. The consistency of the focal mechanisms with each other and the en-echelon pattern of epicenters imply a homogenous stress field and a discontinuous fault structure. The 100-km-long linear belt of seismicity in an area with no throughgoing fault structure is interpreted as a basin-and-range normal fault beginning to form within the Sierra Nevada.

### INTRODUCTION

The Basin and Range tectonic province extends for more than 1500 km along the western Cordillera of North America. The west boundary of this province is generally considered to be at the east front of the Sierra Nevada, and the east boundary at the Colorado Plateau and the west front of the Wasatch Range based on the presence of basin-and-range style tectonic structures (e.g., Wallace, 1984). However, contemporary seismicity and microfault structures suggest basin-and-range extensional tectonics could be expanding to the east (e.g., Smith and Sbar, 1974; Best and Hamblin, 1978) and west (e.g., Lockwood and Moore, 1979; Hill *et al.*, 1984) of these boundaries.

This report presents seismic evidence of basin-and-range deformation west of the Basin and Range Province within the southern part of the Sierra Nevada Mountains. An extensive earthquake swarm occurred at Durrwood Meadows in the southern Sierra Nevada, beginning in October 1983 (Figure 1). This swarm occurred within a 100-km-long linear belt of seismicity that trends north-south through the Sierra Nevada, approximately parallel to and 30 km west of the Sierran frontal fault (Figure 2). This southern Sierra Nevada seismic belt has been the site of six  $M_L \geq 4.0$  earthquakes in the past 50 yr. The rate of seismic activity in this belt was one of the highest in southern California during 1984, and the focal mechanisms of the Durrwood Meadows earthquakes are consistent with pure normal faulting and east-west extension (the same as in adjacent areas of the Basin and Range).

The Durrwood Meadows swarm was centered at latitude  $35^{\circ}55'N$ , longitude  $118^{\circ}19'W$ , about 70 km north of the south edge of the Sierra Nevada. The

predominant fault within the southern Sierra Nevada is the Kern River fault, which extends for more than 150 km along a north-southward strike (Figure 1). This vertical right-lateral fault is thought to have formed during Mesozoic time (Moore and du Bray, 1978). The fault lies within a large, deep river canyon. A lava flow, 4 m.y. old, in which no offsets have been found, covers the fault at about lat  $36^{\circ}15'N$ , a relation suggesting that the fault is no longer active (Moore and du Bray, 1978). The southern Sierra Nevada seismic belt, in which the Durrwood Meadows swarm occurred, is parallel to but 10 km east of the Kern River fault.

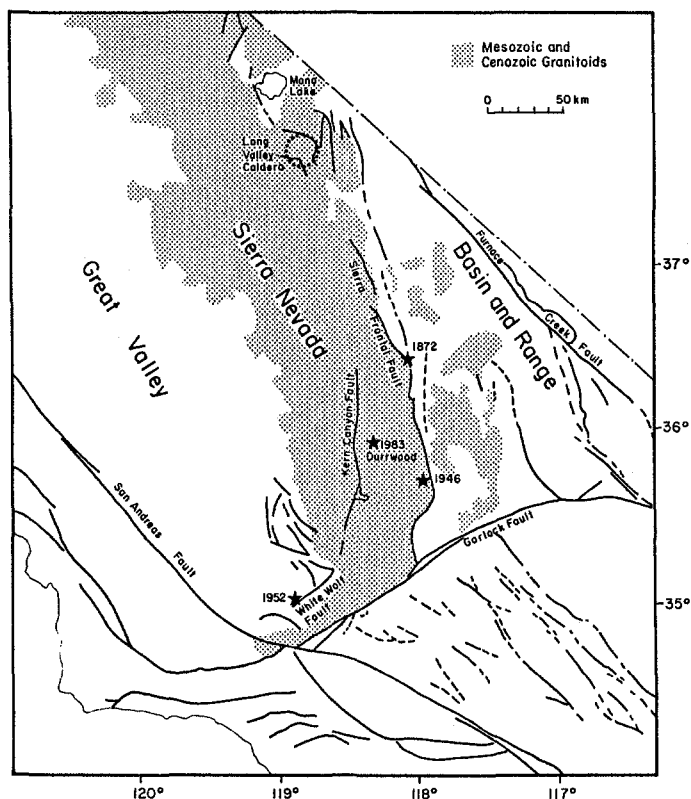


FIG. 1. Eastern California, showing locations of major faults and tectonic provinces. Stars denote major earthquakes of the southern Sierra Nevada, including the 1872 Owens Valley ( $M \sim 8.0$ ), 1946 Walker Pass ( $M_L = 6.4$ ), and 1952 Kern County ( $M_S = 7.7$ ) earthquakes, and the 1983 to 1984 Durrwood Meadows swarm.

Volcanism of Quaternary age has occurred in this area. The Long Valley caldera in the Mammoth area is approximately 150 km north of the swarm. The Coso geothermal area, characterized by Quaternary rhyolite and high heat flow (e.g., Duffield *et al.*, 1980), is 30 km east of the swarm area. A few lava flows of Tertiary age have been documented within the southern Sierra Nevada, including the Golden Trout Creek flow, an unglaciated and, thus, presumably 5,000–10,000-yr-old lava flow that lies along the strike of this seismic lineation (Moore and Lamphere, 1983).

Four large earthquakes have been documented in this region within the historical record. A large earthquake sequence occurred north of the Durrwood Meadows swarm in 1868, but not much is known about it. The largest earthquake in that sequence has been assigned a maximum Modified Mercalli intensity of IX, and earthquakes could be felt for several weeks after the largest event. Reports from an

expedition camping in the Kern Canyon at that time suggest that the sequence was located very near the north end of the canyon (Townley and Allen, 1939) and thus could have been in the southern Sierra Nevada seismic lineation. About 4 yr after this swarm occurred, in 1872, the Owens Valley fault of the Sierran frontal-fault system ruptured for more than 100 km northward from latitude  $36^{\circ}30'N$ , generating an  $M$  8 earthquake (Richter, 1958). Details of this earthquake are also fragmentary, but geologic evidence suggests that it showed right-lateral oblique normal slip (Oakeshott *et al.*, 1972; Lubetkin and Clark, 1985).

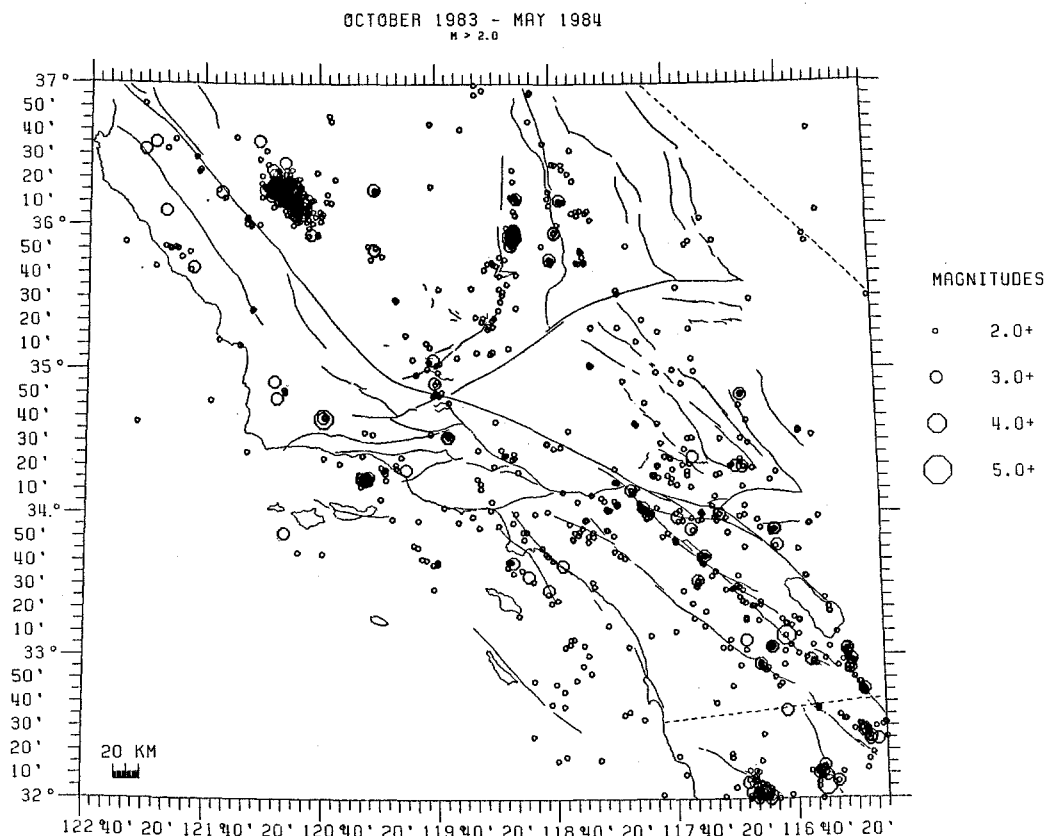


FIG. 2. Catalog locations of all  $M_C \geq 2.0$  earthquakes recorded by the CIT-USGS seismic network in southern California between October 1983 and May 1984.

The largest earthquake ( $M_L = 6.3$ ) recorded within the southern Sierra Nevada proper was the 1946 Walker Pass earthquake (Chabrabarty and Richter, 1949), which was notable for its large foreshock ( $M_L = 5.4$ ) and very rich aftershock sequence. Although the causative fault has not yet been recognized, recent relocations of the event with respect to modern earthquakes have confirmed that the Walker Pass event occurred within the Sierra Nevada and not along or east of the frontal fault (R. S. Dollar, unpublished data, 1985). The aftershocks of the 1952 Kern County earthquake ( $M_S = 7.7$ ) also extended into the western foothills of the Sierra Nevada. This event exhibited left-lateral oblique thrusting, in contrast to earthquakes in the Sierra and to the east, where normal and right-lateral strike slip are the predominate modes of deformation.

The largest earthquake in the Durrwood Meadows swarm itself had a local magnitude, from Wood-Anderson instruments in southern California, of  $M_L = 4.5$ . The local magnitude, determined using northern California stations, was  $M_L = 5.0$  (J. P. Eaton, personal communication, 1985). This swarm was a major sequence, with more than 2,000 earthquakes recorded between October 1983 and May 1984. This report presents relocations of the swarm and nearby earthquakes from October 1983 to May 1984, and focal mechanisms of all  $M_L \geq 3.0$  events within the swarm. We also discuss the tectonic significance of these results and their implications for seismic-hazard estimates in the region.

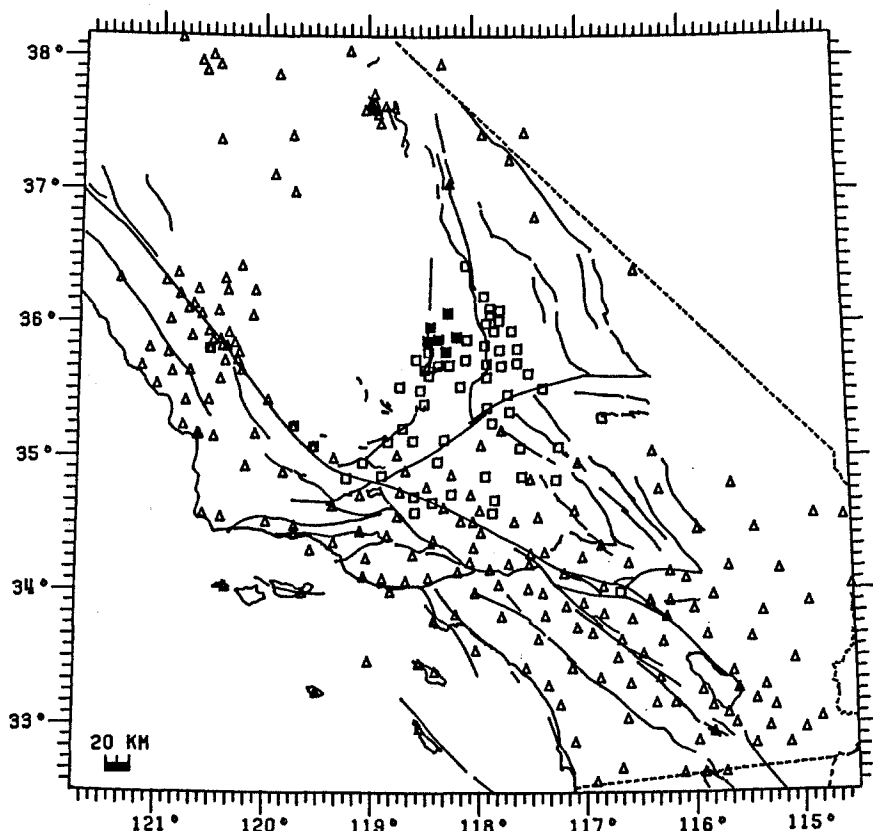


FIG. 3. Schematic map of study area, showing locations of seismic stations used in this study. Open squares are stations used to locate the earthquakes. Triangles are stations used only for focal mechanisms. Solid squares are portable stations installed from 28 October to 15 November 1983.

### DATA

The Durrwood Meadows earthquakes were recorded by the 250 station southern California network operated jointly by the California Institute of Technology (CIT) and the U.S. Geological Survey (USGS). The more than 50 stations in this network that were used to locate the Durrwood Meadows swarm are all within 105 km of the swarm (Figure 3). Seismic signals are digitized at 62.5 samples/sec in real time and processed using the CUSP system of Johnson (1983). Arrival times for  $P$  and  $S$  waves ( $S$  waves are read for about 10 per cent of the stations) are picked by humans through an interactive computer system, usually with an accuracy of 0.02 sec. In late October 1983 (9 days after the start of the Durrwood Meadows swarm),

six portable seismographs that record analog data on magnetic tape were installed in the Durrwood Meadows area and maintained there for several weeks (J. P. Eaton, personal communication, 1984) (Figure 3).

All of the earthquakes recorded by the CUSP system in the southern Sierra Nevada between October 1983 and May 1984 were relocated, using the recorded arrival times. Focal mechanisms were determined from *P*-wave first motions for all 35 of the  $M_L \geq 3.0$  earthquakes that occurred during that time. The first motions and *P*- and *S*-wave arrivals of all 35 events at all stations in the southern California network were reread for this study from digital records. In addition, first motions from 50 stations in central California and 12 stations in the Mammoth area of the Calnet system operated by the USGS were read from records made with an analog playback system. Thus, from 100 to 200 first motion records have been read specifically for this study for each  $M_L \geq 3.0$  event in the swarm. The locations of stations used for the focal mechanisms but not for locating the earthquakes are shown in Figure 3.

The model of seismic velocities used to locate these earthquakes is model A in Table 1. It is based on the model for the southern Sierra Nevada by J. P. Eaton

TABLE 1  
SEISMIC-VELOCITY MODELS USED TO LOCATE EARTHQUAKES IN THE DURRWOOD MEADOWS SWARM AND TO COMPUTE TAKEOFF ANGLES\*

Model A		Model B		Model C	
<i>P</i> -Wave Velocity (km/sec)	Depth to Top of Layer (km)	<i>P</i> -Wave Velocity (km/sec)	Depth to Top of Layer (km)	<i>P</i> -Wave Velocity (km/sec)	Depth to Top of Layer (km)
3.5	0	3.5	0	3.5	0
5.8	1	5.8	1	5.8	1
6.2	8	6.2	8	6.2	8
6.9	22	6.9	22	6.9	22
7.9	36	7.9	40	7.9	32

\* Model A was used for locations and for takeoff angles of stations in most of southern California. Model B was used for takeoff angles at stations in the Coast Ranges and the northern Sierra. Model C was used for takeoff angles at stations in the eastern Mojave Desert.

(personal communication, 1984) and was tested for minimum travel-time residuals against several other models on a group of 20 well-located events that had been recorded by the close-in temporary stations.

The takeoff angles of the ray paths depend on the velocity structure in the source region. However, which ray arrives first at a given station depends on the velocity structure along the total travel path. The depth to the Moho in the Sierra Nevada is large for California, 40 to 55 km (Hill, 1978). Some stations (e.g., the Mammoth area stations) received rays that followed a completely Sierran path, and others (e.g., the Mojave Desert stations) received rays that followed a path along which the Moho shallows quickly.

To determine which path the first arriving rays followed, we constructed plots of the reduced traveltimes versus distance. Figure 4 (left) plots the travel times for the more than 4,000 timed arrivals of  $M_L \geq 3.0$  earthquakes in the Durrwood Meadows swarm, reduced with a velocity of 7.9 km/sec (the mantle velocity in the model). Also in Figure 4 (right), the arrivals for all the events are averaged at each station. In both figures, the symbol used to plot an arrival is a function of the azimuth of a ray from the earthquake source to the station. These plots show a strong azimuthal

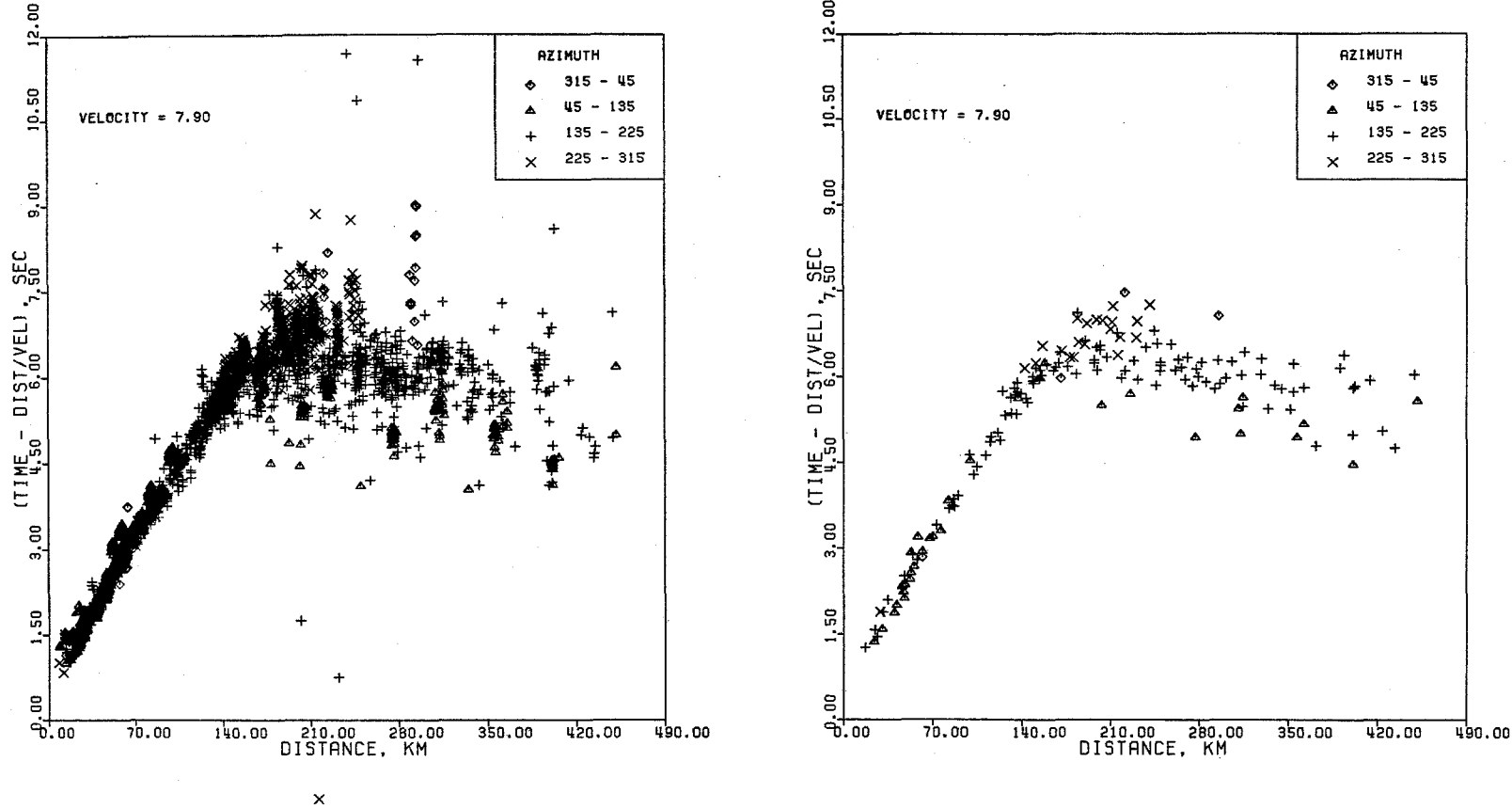


FIG. 4. Distance between earthquake and station versus  $P$ -wave travel time minus the distance divided by 7.9 km/sec (the mantle velocity under the Sierra Nevada) for (left)  $P$ -wave arrivals of all 35  $M_L \geq 3.0$  earthquakes in the Durrwood Meadows swarm and (right)  $P$ -wave arrivals averaged over all earthquakes at each station. Symbol type depends on azimuth of ray from earthquake to station.

dependence in the distribution of travel times, particularly in the cross-over distance from crustal to Moho refractions.

Three crustal models (as listed in Table 1) have been used to account for the differences in travel time. The only difference between the models is the depth to the Moho, which ranges from 32 to 40 km. Model A was used to locate all of the earthquakes and to determine the takeoff angles for southern stations; model B, which uses a deeper depth to the Moho, was used to determined the takeoff angles for Coast Ranges and Sierra Nevada stations; and model C, which uses a shallower depth to the Moho, was used to determine the takeoff angles for Mojave Desert

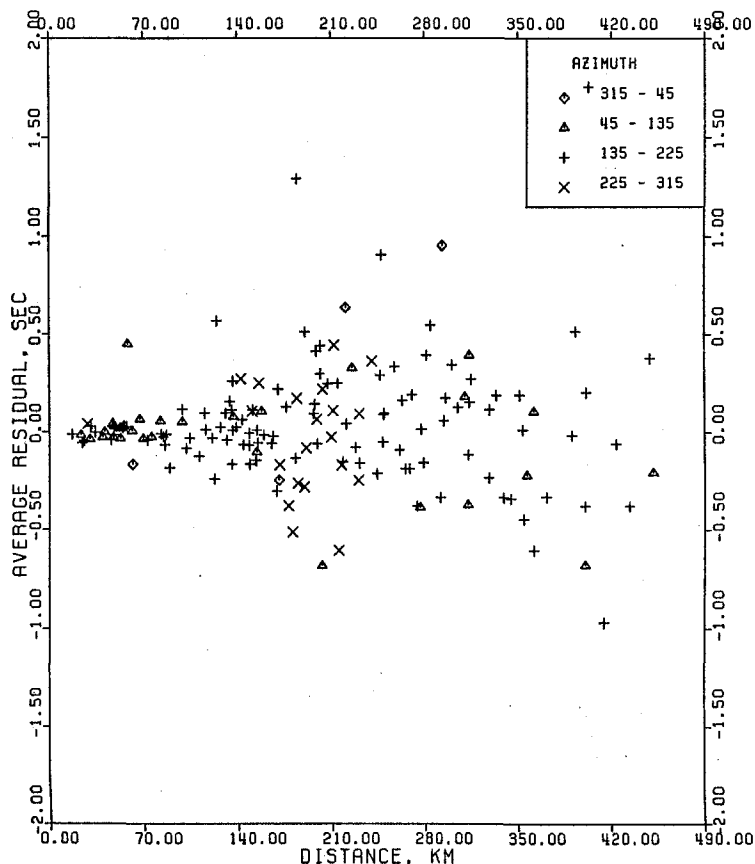


FIG. 5. Calculated travel-time residual (calculated minus observed travel time) at each station versus distance from Durrwood Meadows earthquakes to the station, averaged over all 35  $M_L \geq 3.0$  earthquakes. Symbol type depends on azimuth of ray from earthquake to station.

stations. The average residuals (the differences between observed and calculated travel times averaged over all 35 events) calculated using these models at each station are plotted versus distance in Figure 5. The lack of systematic variation in Figure 5 shows that the models used have adequately accounted for the azimuthal variations in travel time.

A master-event technique was used to locate the earthquakes. The earthquake location computer program HYPOINVERSE (Klein, 1978) was used with a single-velocity model and with travel-time delays applied to each station. The station delays used were the travel-time residuals of an  $M_L = 3.7$  earthquake that occurred on 7 November 1983, which was well recorded by the portable stations. Seven

stations were within 20 km of the hypocenter of this event, and the location was accurate to within 300 m horizontally and 500 m vertically (32 per cent confidence limit, assuming a reading error of 0.035 sec). Using this master-event technique and the velocity model described above, the errors in location relative to the master event were less than 500 m horizontal error and 1 km vertical error for most events in the Durrwood Meadows area, including all the  $M \geq 3.0$  earthquakes.

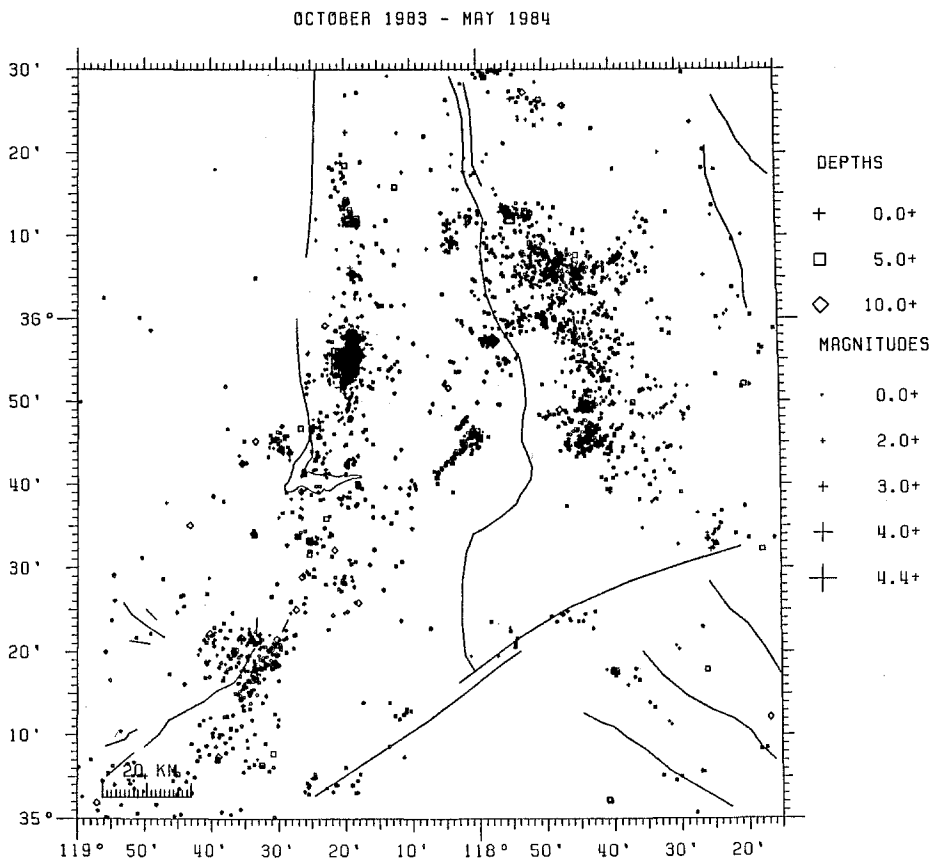


FIG. 6. Schematic map showing relocated epicenters of all earthquakes recorded in the southern Sierra Nevada between October 1983 and May 1984.

## RESULTS

*Earthquake locations.* The Durrwood Meadows swarm was located within the Sierra Nevada batholith (Figure 6), within a linear belt of seismicity that trends north-south, is parallel to but 10 to 15 km east of the Kern River fault and 30 km west of the Sierran frontal fault. Within this seismic lineation, the level of microearthquake activity was as high as or higher than anywhere in southern California during 1984. At its south end, this seismic belt joins with the aftershock zone of the 1952 Kern County  $M_S = 7.7$  earthquake on the White Wolf fault. The north end of the seismic belt stops abruptly at latitude  $36^{\circ}30'N$ , 30 km west of the south end of the 1872 Owens Valley rupture.

The historical catalog of southern California earthquakes compiled by the CIT suggests that this lineation has been a predominant feature of past earthquake activity. Figure 7 shows the locations of all the  $M_L \geq 3.5$  earthquakes that occurred



from 1960 to 1984. Most of these events occurred within the seismic belt; the only other site of moderate earthquakes during this period in the southern Sierra Nevada is the aftershock zone of the 1946 Walker Pass earthquake. Most of the earthquakes within the lineation appear to have been in swarms similar to temporal distribution to the Durrwood Meadows swarm.

The Durrwood Meadows swarm began in October 1983; its highest level of activity was between October 1983 and May 1984. The number of earthquakes per day during this period is plotted in Figure 8. Five periods of a few days each had high

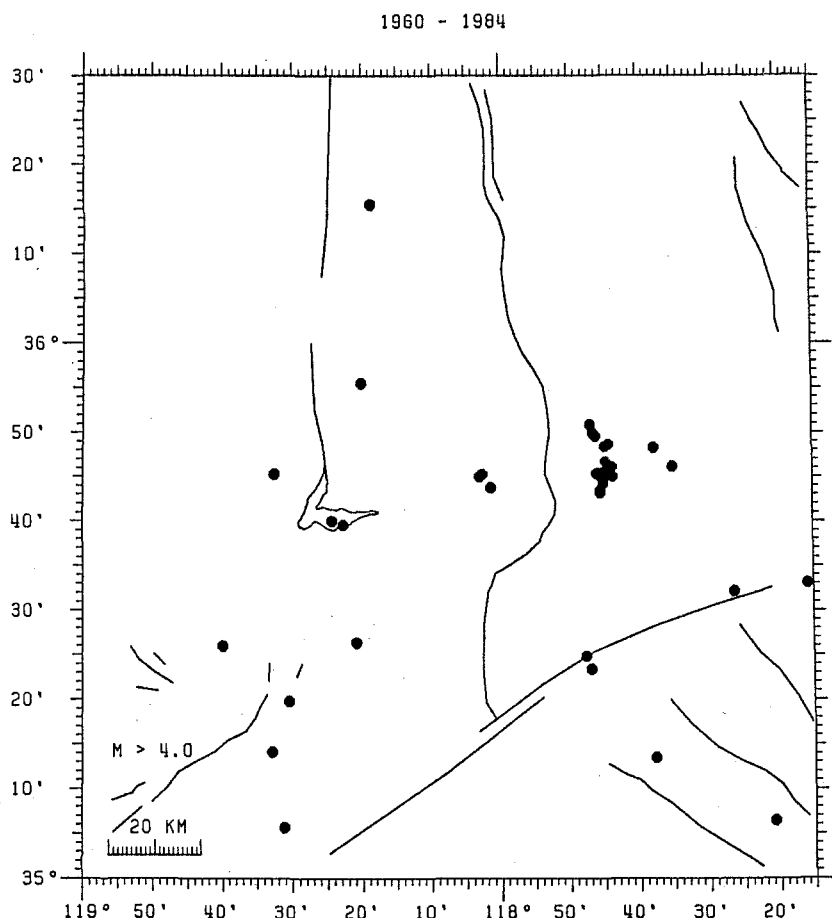


FIG. 7. Schematic map showing locations of all  $M_L \geq 3.5$  earthquakes in CIT catalog for the southern Sierra Nevada between 1960 and 1984.

levels of seismic activity and included most of the  $M_L \geq 3.0$  earthquakes of the swarm. The spatial distributions of the earthquakes varied between these five periods. Figure 9 shows the epicentral distribution of the swarm during successive periods of time.

The Durrwood Meadows swarm started on 19 October 1983, with an  $M_L = 4.0$  earthquake. The largest earthquake ( $M_L = 4.5$ ) within the swarm occurred 56 hr later on 21 October. During the first 5 days, earthquakes occurred along a northwestward trend (Figure 9a). The epicenters were tightly clustered, lying within a  $1 \times 3$ -km ellipse. Six  $M_L \geq 3.0$  earthquakes occurred on 25 October, extending the

area of seismic activity to the south (Figure 9b). Throughout this period, the epicenters continued to strike northwest.

A third period of high seismic activity began 6 November with three  $M_L \geq 3.0$  earthquakes (Figure 9c). Unlike the earlier events, which occurred along a northwestward trend, the earthquakes in November showed a distinct northeastward trend. This new trend branches off from the original northwest-trending lineation to form a Y-shaped structure. The latest two periods of high seismicity were in early January and late March 1984. Earthquakes during both these periods occurred north of previous activity in small clusters and have vague northwestward or north-southward strikes (Figure 9, d and e).

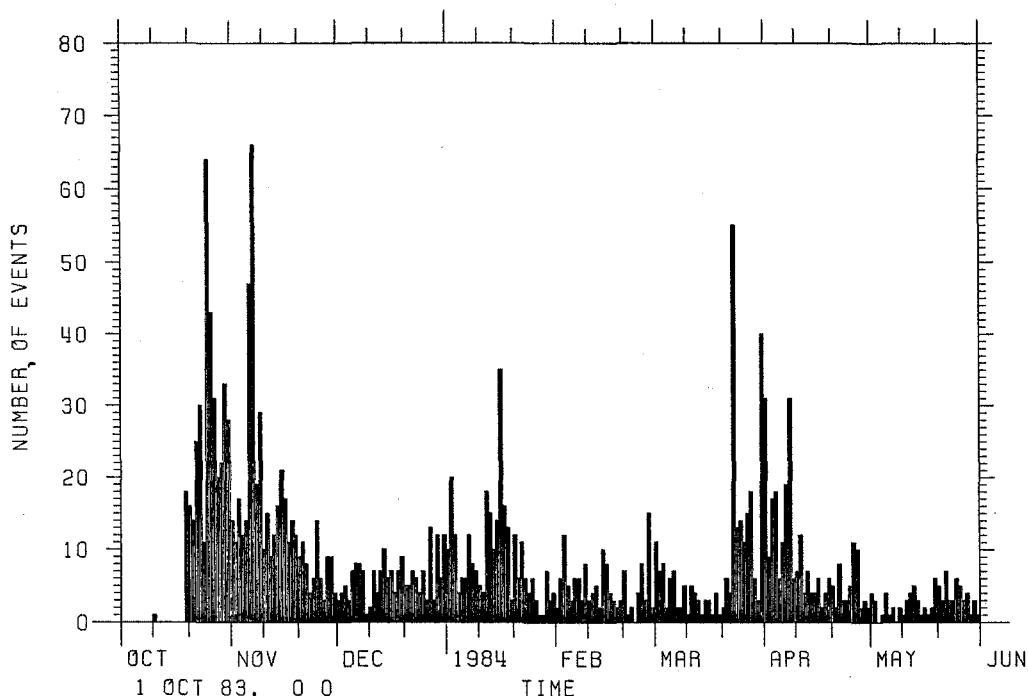


FIG. 8. Number of earthquakes of all magnitudes in the Durrwood Meadows swarm, recorded per day between latitude  $35^{\circ}51'$  and  $36^{\circ}0'N$  and between longitude  $118^{\circ}23'$  and  $118^{\circ}16'W$ .

The epicentral distribution of the Durrwood Meadows swarm (Figure 9f) shows a complex pattern. Each of the five periods of high seismic activity occurred at different locations and had different epicentral distributions. The first 3 months of the swarm together form a Y-shaped distribution of earthquakes. Later activity was offset a few kilometers to the north.

The depth distribution of the swarm is relatively simple. Figure 10 (a to f) shows the depths of the Durrwood Meadows earthquakes, projected along a southwest-northeast line, for the five time periods discussed above and the whole swarm. All of the calculated earthquake depths lie between 0 and 6 km. A map and cross-section of only the high-quality hypocenters (Figure 11), in fact, suggests that all of the earthquakes occurred between 3- and 6-km depth. The depths of the larger events ( $M_L \geq 3.0$ ) are even more tightly constrained; all but one occurred between 4.0 and 5.6 km. The only evident variation in the depth distribution is that the  $M_L \geq 3.0$  earthquakes in each successive burst of activity occurred at a slightly shallower

depth than the previous events (Figure 11). The larger events on the original northwestward trend are between 5.0- and 5.6-km depth, whereas the events in the northeast branch of the Y are between 4.5- and 5.0-km depth. Later events that occurred north of the Y-shaped structure are between 4.0- and 4.5-km depth. Because of the northerly migration of the swarm, this pattern suggests a general shallowing of seismicity to the northeast.

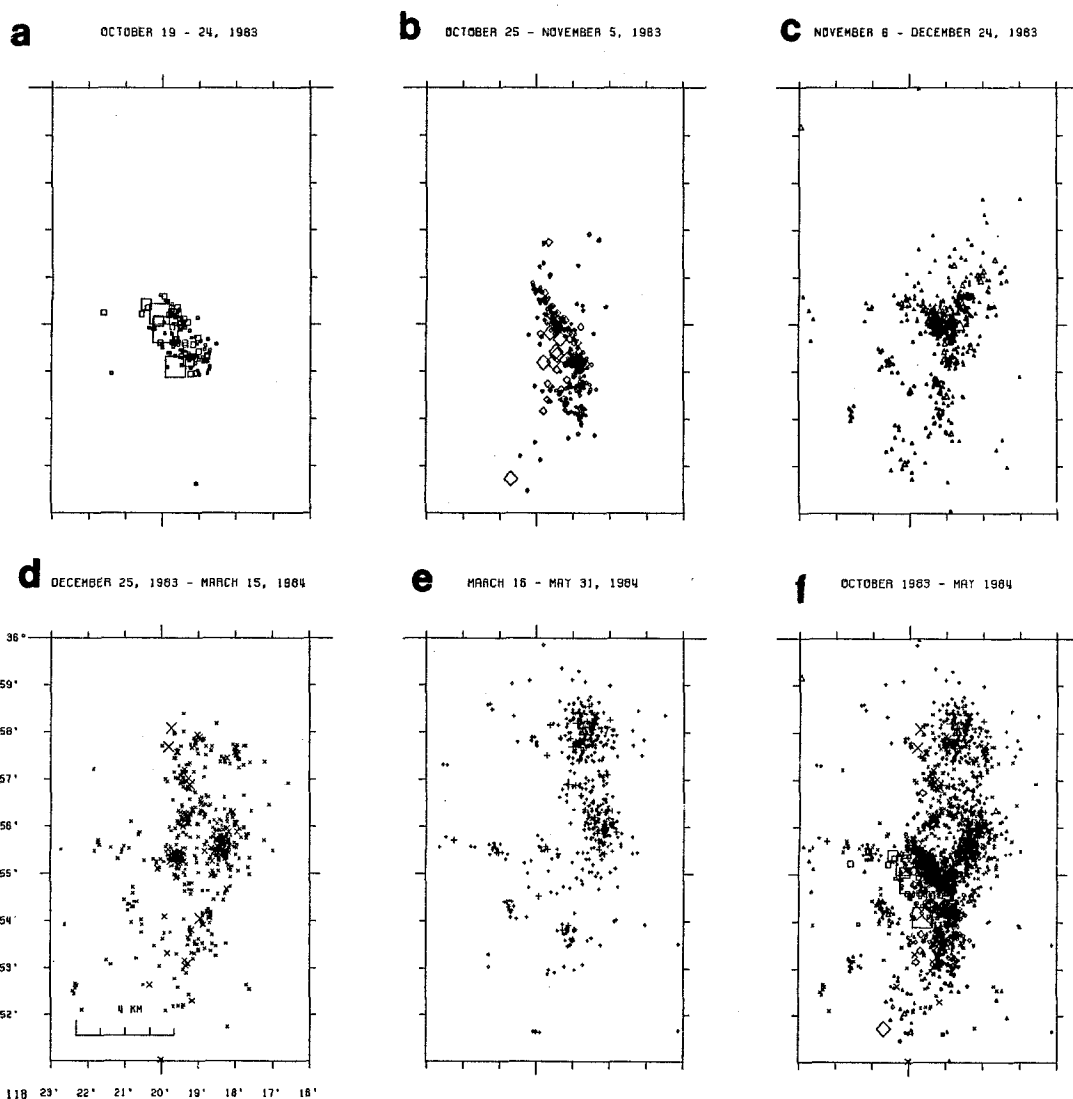


FIG. 9. Schematic maps of the relocated epicenters of all earthquakes recorded in the Durrwood Meadows area during: (a) 19-24 October 1983; (b) 25 October-5 November 1983; (c) 6 November-24 December 1983; (d) 25 December 1983-15 March 1984; (e) 16 March-31 May 1984; and (f) the total time period October 1983-May 1984. Symbol types, which increase in size with magnitudes, depend on which of these five time periods the earthquakes occurred in.

Although various clusters and lineations are evident in the locations of the swarm events, slip must have occurred on many different planes during the swarm. The absence of large earthquakes and the limiting of depths to the range of 3 to 6 km suggest that the planes which slipped in the swarm were relatively small and

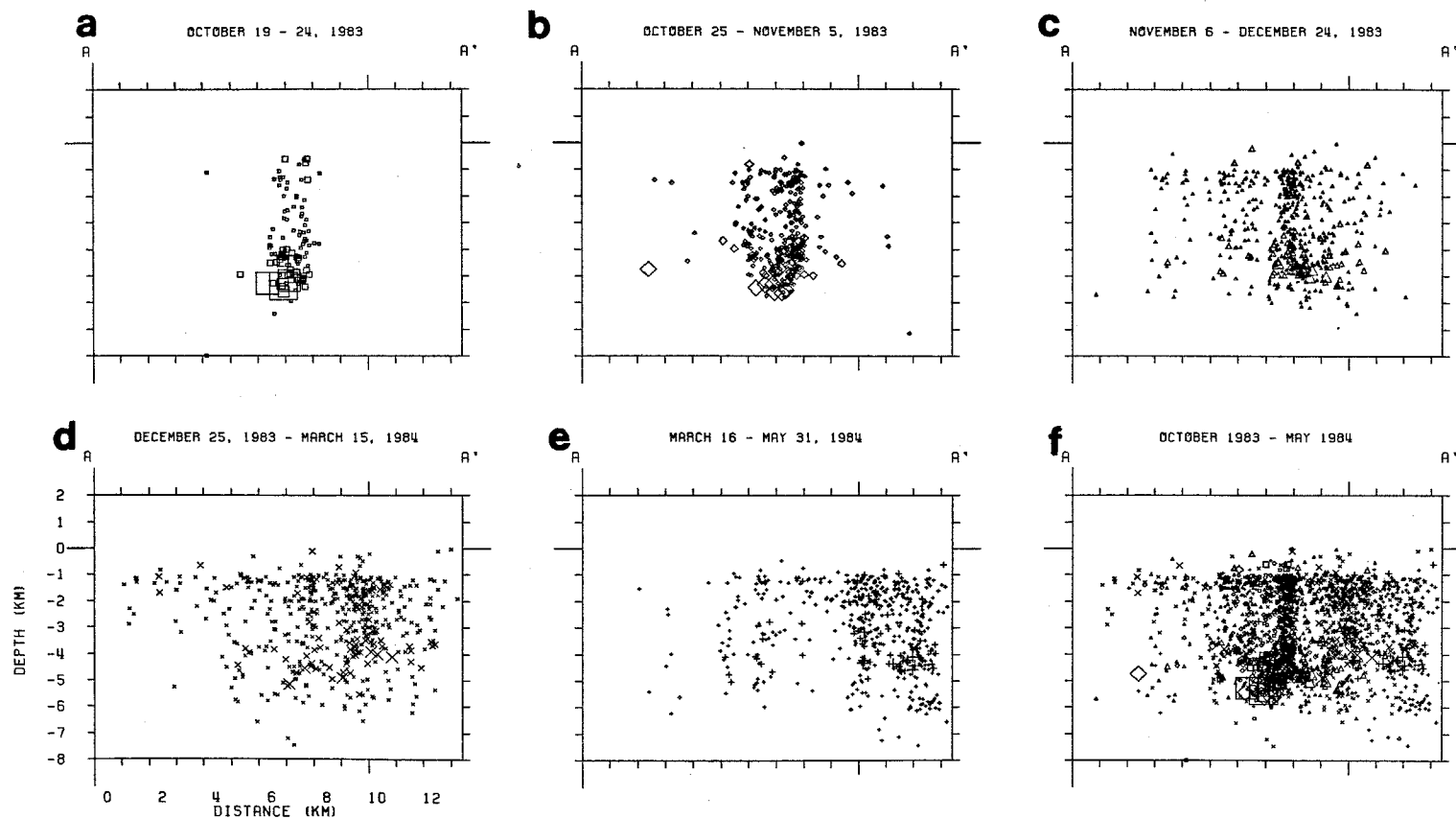


FIG. 10. Located depths of the Durrwood Meadows earthquakes, projected along a line striking N38°E. (A-A', Figure 11.) Symbol types and time periods same as in Figure 9.

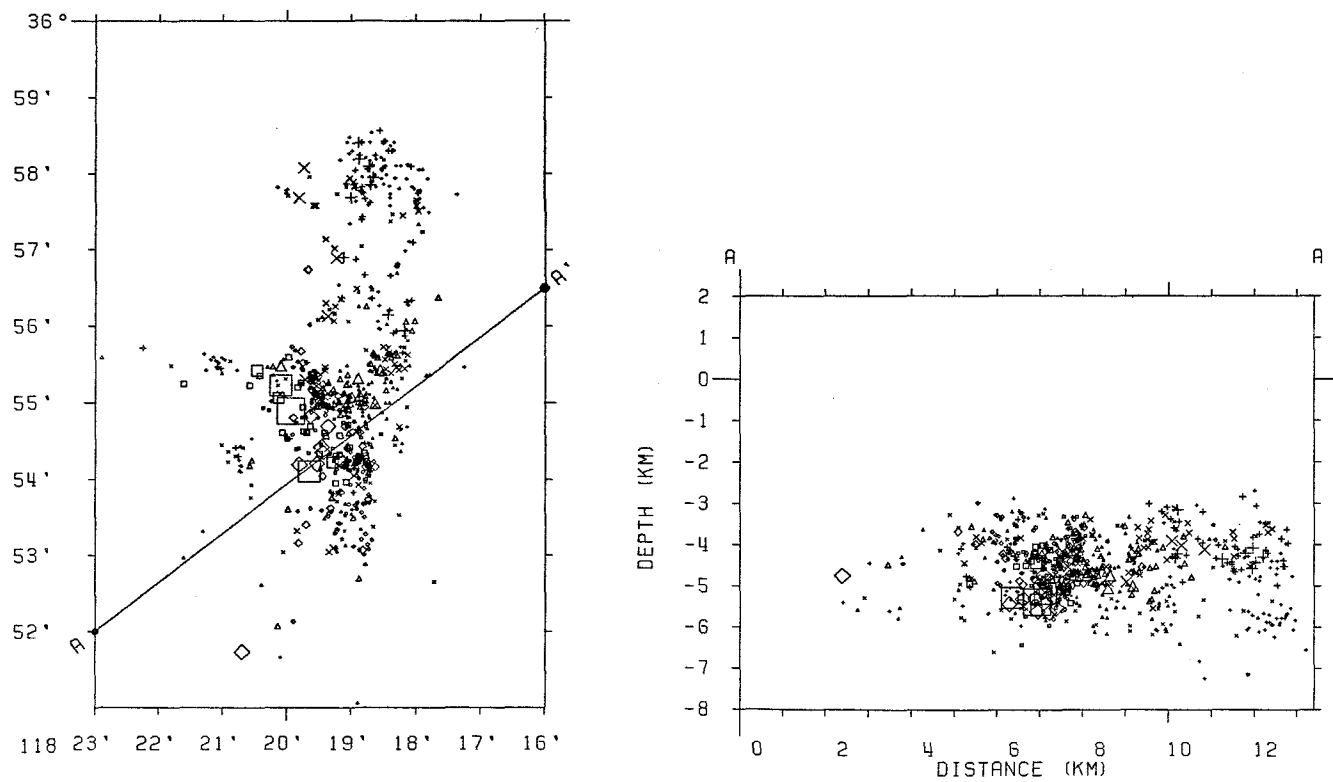


FIG. 11. (Left) Schematic map of epicenters of all Durrwood Meadows earthquakes from October 1983 to May 1984, with a calculated horizontal error less than 0.5 km and a calculated vertical error less than 1.0 km. (Right) Depths of Durrwood Meadows earthquakes (on the left) plotted against projection of epicenters onto line A-A'.

probably did not extend to the surface. Most other earthquakes in the southern Sierra Nevada are not so shallow as the Durrwood Meadows swarm. The larger earthquakes in the Lake Isabella area south of the swarm and in the Walker Pass area east of the Durrwood Meadows swarm commonly have depths in the range of 5 to 10 km (Dollar, unpublished data, 1985).

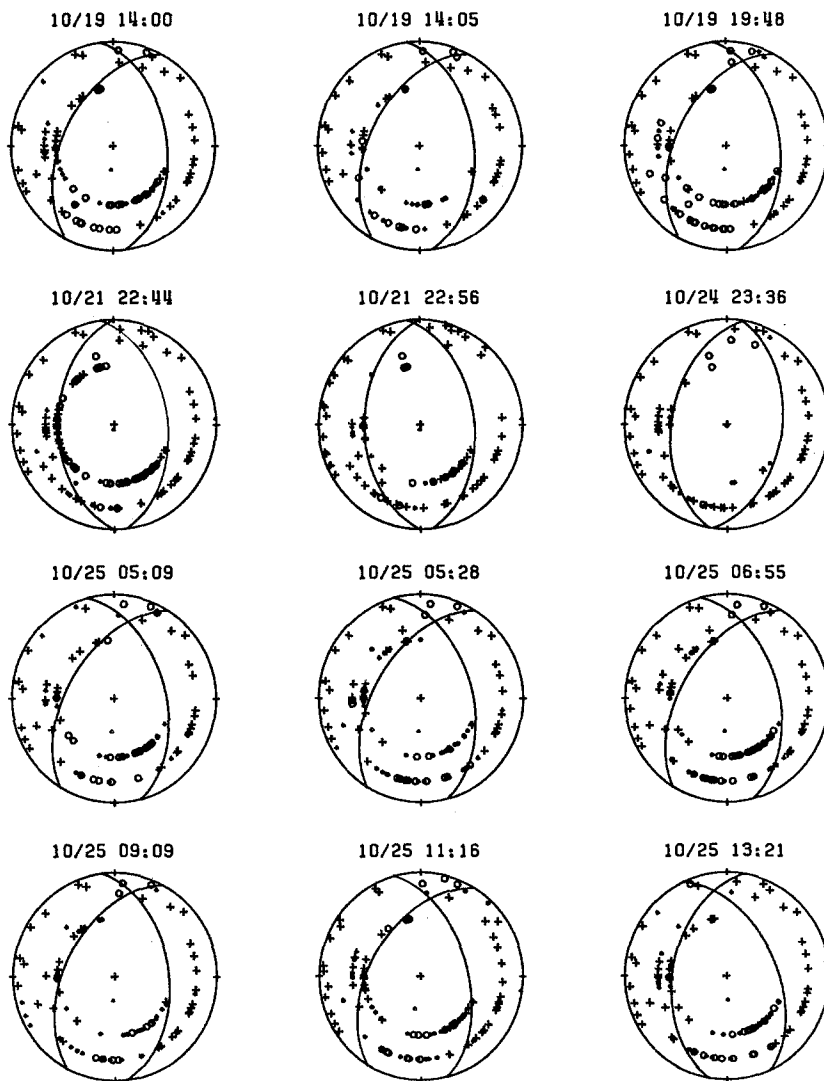


FIG. 12. Equal-area lower-hemisphere projections of  $P$ -wave first motions recorded for the first 12  $M_L \geq 3.0$  earthquakes at Durrwood Meadows. Crosses, compressive first motions; circles, dilatant first motions. Smaller symbols denote less reliable readings. Best-fitting focal-mechanism solution for each event (listed in Table 2) is also shown. The 35  $M \geq 3.0$  earthquakes are in chronological order in Figures 12 to 14.

*Earthquake focal mechanisms.* The single-event focal mechanisms determined from  $P$ -wave first-motion data for all of the  $M_L \geq 3.0$  earthquakes of the Durrwood Meadows swarm are shown in Figures 12 to 14 and listed in Table 2. All of these focal mechanisms are very well constrained, in that changes of only a few degrees in the mechanisms would produce significantly more violations in the compressional

and dilational quadrants. However, none of the mechanisms can be fitted by two orthogonal planes without some incompatible readings. We note that all of the first motions used were read specifically for this study. No ambiguous readings were used, and all of the readings in violation were rechecked. The incompatible first motions appear in every mechanism but are more common in those mechanisms with the smallest amounts of oblique strike-slip movement.

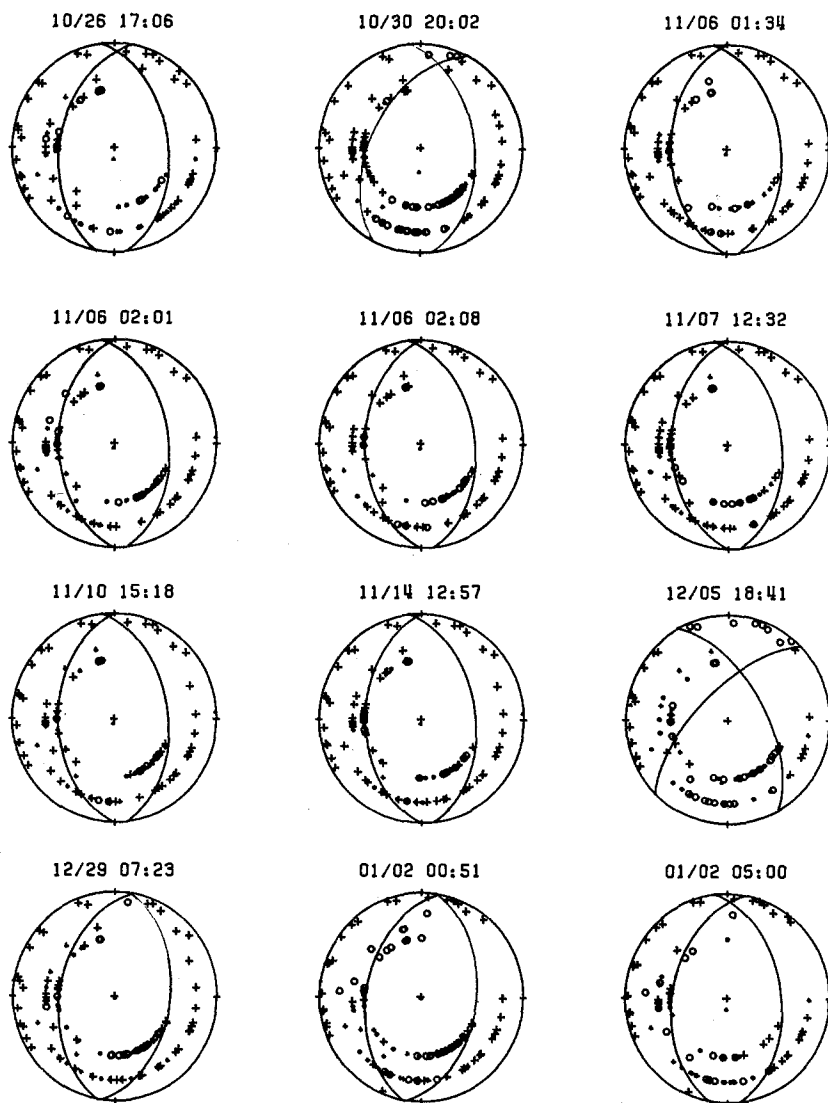


FIG. 13. Lower-hemisphere projections of  $P$ -wave first motions for 12 Durrwood Meadows earthquakes. Same conventions as in Figure 12.

Figure 15 shows the location of epicenters of the  $M_L \geq 3.0$  events and the mechanisms of all the events. The mechanisms are all similar and show nearly pure normal slip along planes striking north-south or north-northwest. Two mechanisms account for 14 of the earthquakes, and more than half of the events have one plane striking at  $N7^\circ W$  and dipping  $46^\circ E$ . All of the events from October to February

have an east-dipping plane with a strike between N25°W and N8°E. Slightly greater variation in the orientation of the west-dipping plane than of the east-dipping plane results in varying but small amounts of right-lateral slip on the east-dipping plane.

The only significant change in the focal mechanisms appeared toward the end of the swarm (late March 1984) when the epicenters of events were located several

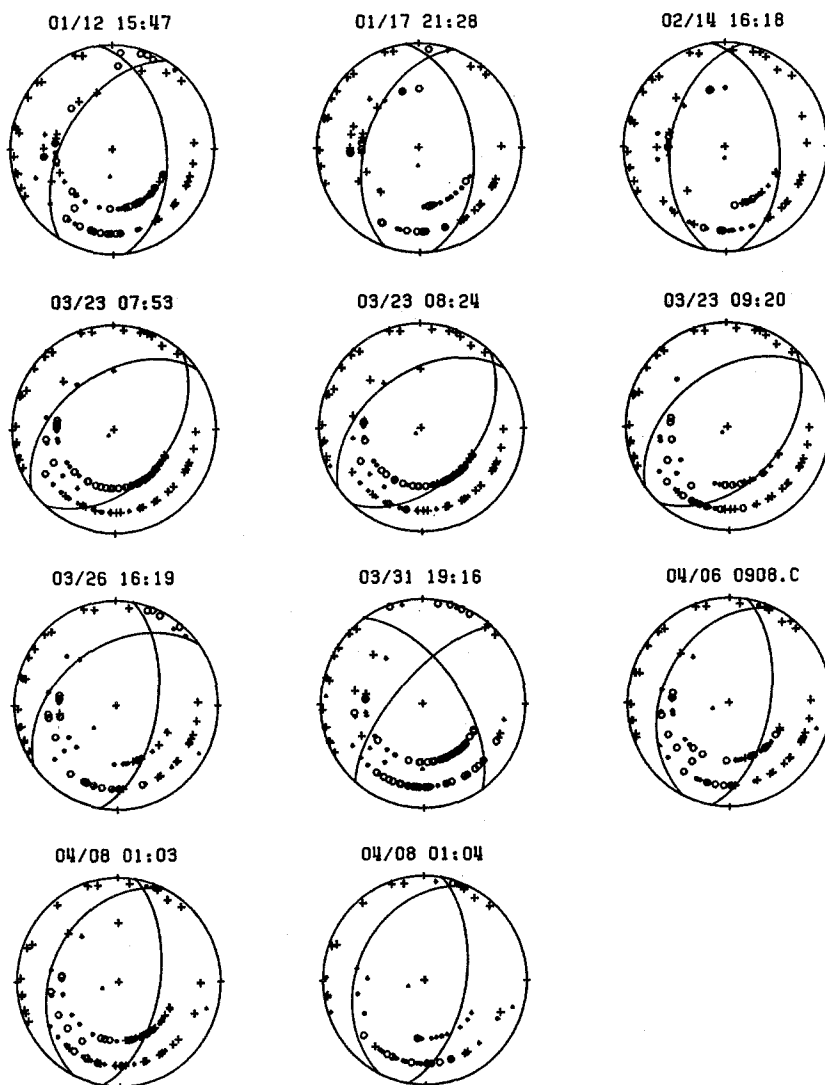


FIG. 14. Lower-hemisphere projections of  $P$ -wave first motions for 11 Durrwood Meadows earthquakes. Same conventions as in Figure 12.

kilometers north of the previous activity. Four of the  $M_L \geq 3.0$  events that occurred at that time, while still showing almost pure normal motion, had planes striking northeast rather than north-south. This was also the only time when the epicentral distribution showed a north-southward strike.

Although the earthquakes with northeast-striking focal mechanisms are spatially separate from the other events, the distance between the different types of events is only a few kilometers. The  $P$  axis is vertical for all of these events, but the  $T$  axis



varies by more than  $50^\circ$  between the earthquakes of October through February and the events of late March. So large a variation in the  $T$  axis over such small temporal and spatial separations suggests that the magnitudes of the principal horizontal stresses are similar (Angelier, 1984). Similar horizontal stresses would allow the minimum and intermediate stresses to flip as a result of small changes in the stress field.

TABLE 2  
HYPOCENTRAL PARAMETERS AND FOCAL MECHANISMS DETERMINED FOR ALL  $M_L \geq 3.0$   
EARTHQUAKES IN THE DURRWOOD MEADOWS SWARM

Date (yr/mo/day)	Time (UTC)	Magnitude	Location		Depth (km)	Plane 1			Plane 2	
			Latitude ( $^\circ$ N)	Longitude ( $^\circ$ W)		Strike	Dip	Rake	Strike	Dip
83/10/19	14:00	4.0	35°55.2'	118°20.1'	5.2	353.0	46.0	64.1	208.0	49.7
83/10/19	14:05	3.4	55.4	20.5	5.6	353.0	46.0	64.1	208.0	49.7
83/10/19	19:48	3.8	55.1	20.1	5.3	353.0	46.0	64.1	208.0	49.7
83/10/21	22:44	4.5	54.9	19.9	5.4	353.0	46.0	85.1	180.0	44.2
83/10/21	22:56	3.3	54.2	19.3	4.4	353.0	46.0	85.1	180.0	44.2
83/10/24	23:36	4.0	54.1	19.6	5.3	8.0	45.0	88.6	190.0	45.0
83/10/25	5:09	3.5	54.3	19.4	5.3	345.0	48.0	54.3	212.0	52.9
83/10/25	5:28	3.2	54.2	19.5	5.3	345.0	48.0	54.3	212.0	52.9
83/10/25	6:55	3.8	54.4	19.5	5.6	345.0	48.0	54.3	212.0	52.9
83/10/25	9:09	3.1	54.8	19.6	5.6	353.0	46.0	64.1	208.0	49.7
83/10/25	11:16	3.8	51.7	20.7	4.8	345.0	52.0	56.6	212.0	48.9
83/10/25	13:21	3.5	54.7	19.4	5.5	335.0	50.0	65.8	190.0	45.7
83/10/26	17:06	3.1	54.3	19.2	4.7	353.0	46.0	65.8	190.0	45.3
83/10/30	22:02	3.6	54.2	19.8	5.4	353.0	46.0	64.1	200.0	49.7
83/11/06	1:34	3.1	55.1	19.1	4.7	353.0	46.0	85.1	180.0	44.2
83/11/06	2:01	3.0	55.0	19.0	4.7	353.0	46.0	85.1	180.0	44.2
83/11/06	2:08	3.1	55.1	19.0	4.8	353.0	46.0	85.1	180.0	44.2
83/11/07	12:32	3.7	55.3	18.9	4.7	353.0	46.0	85.1	180.0	44.2
83/11/10	15:18	3.0	55.4	18.6	5.0	353.0	46.0	85.1	180.0	44.2
83/11/14	12:57	3.3	55.0	18.6	5.0	353.0	46.0	85.1	180.0	44.2
83/12/05	18:41	3.1	55.5	20.1	4.5	330.0	60.0	28.2	225.0	56.9
83/12/29	7:23	3.3	54.0	19.0	5.2	8.0	45.0	88.6	190.0	45.0
84/01/02	0:51	3.4	58.1	19.7	4.1	8.0	45.0	88.6	190.0	45.0
84/01/02	5:00	3.2	57.7	19.8	4.0	353.0	46.0	78.0	190.0	45.3
84/01/12	15:47	3.1	55.3	19.7	4.5	353.0	46.0	60.6	212.0	52.9
84/01/17	21:28	3.0	56.9	19.2	3.9	353.0	46.0	70.5	200.0	47.8
84/02/14	16:18	3.1	56.1	19.4	4.9	353.0	46.0	78.0	290.0	45.3
84/03/23	7:53	3.8	58.2	18.9	4.1	43.0	45.0	81.5	235.0	45.6
84/03/23	08:24	3.8	58.1	18.7	4.4	43.0	45.0	81.5	235.0	45.6
84/03/23	09:20	3.1	57.7	19.0	4.3	43.0	45.0	81.5	235.0	45.6
84/03/26	16:19	3.1	56.2	18.4	4.3	10.0	57.0	61.4	235.0	42.6
84/03/31	19:16	3.6	55.9	18.2	3.2	235.0	60.0	24.8	222.0	68.7
84/04/06	9:08	3.0	56.9	19.1	4.2	10.0	57.0	80.5	207.0	34.2
84/04/08	1:03	3.2	58.0	18.7	4.6	10.0	57.0	80.5	207.0	34.2
84/04/08	1:04	3.2	57.8	18.7	4.2	10.0	57.0	80.5	207.0	34.2

### INTERPRETATION

Three features of the Durrwood Meadows earthquake swarm are distinctive. First, the focal mechanisms of the larger earthquakes within the swarm are nearly identical. Second, the strikes of the distribution of the epicenters do not coincide with the strikes of the focal mechanisms. Third, the swarm occurs within a 100-km-long seismic lineation in an area where no fault has been recognized. These features can be explained by westward growth of the Basin and Range Province

into the Sierra Nevada. In this model, the 100-km-long band of earthquakes represents an early stage in the formation of a new fault.

The Durrwood Meadows swarm showed much less variety in its focal mechanisms than most swarms and aftershock sequences in California (e.g., Weaver and Hill, 1978; Corbett and Johnson, 1982; Johnson and Hill, 1982). These variations are

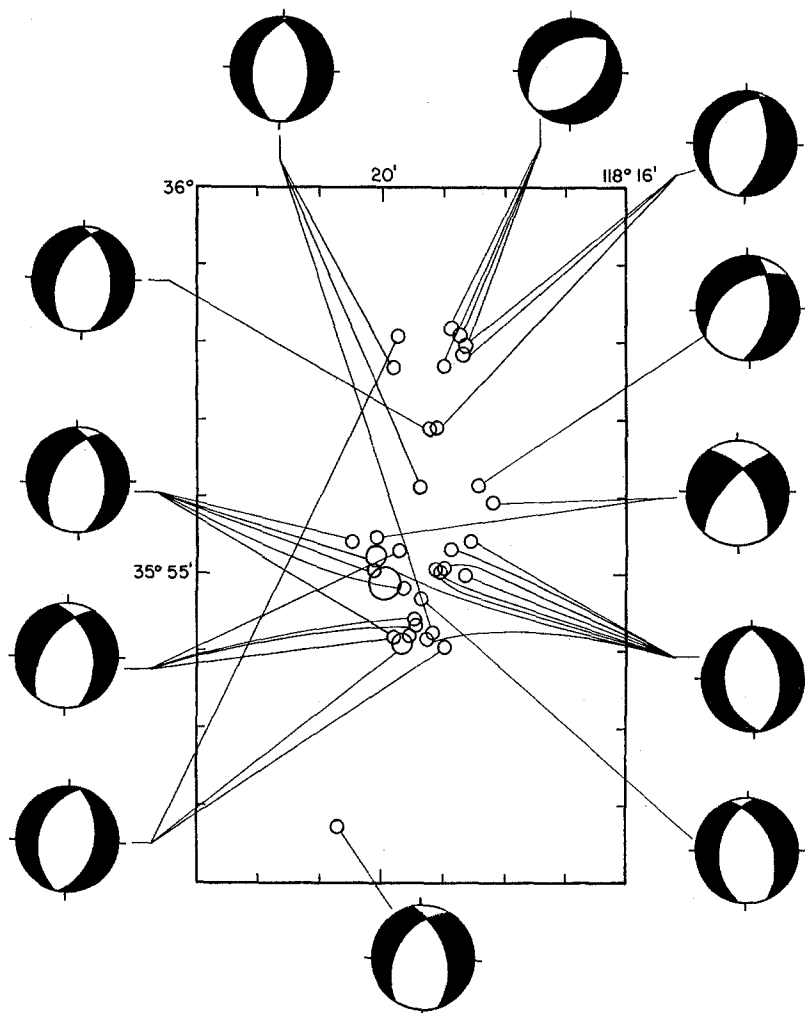


FIG. 15. Schematic map showing locations of all  $M_L \geq 3.0$  earthquakes in the Durrwood Meadows swarm recorded between October 1983 and May 1984, with the focal mechanisms determined for those events.

commonly attributed to faulting along planes that have a wide range of orientations, as well as to small-scale fluctuations in the stress field that bring one plane closer to failure than another.

The consistency of the focal mechanisms at Durrwood Meadows implies that either the stress field is nearly uniform over the swarm region or that only faults oriented N7°W exist in this region. The absence of faults or joints at any other orientation but N7°W seems unlikely. Geologic studies of joints and microfaults in the Sierra Nevada have documented a wide range of joint orientations north of the Durrwood Meadows area; northeast-trending joints are most common (Lockwood and Moore, 1979; Segall and Pollard, 1983). In a nearly homogeneous stress field,

only the fault or joint at the most ideal orientation will fail if all orientations have the same failure strength. Therefore, a uniform stress field in the relatively homogeneous Sierra Nevada seems a more likely explanation for the consistency of the focal mechanisms.

Although a single large fault might explain the consistency of the focal mechanisms, this explanation is precluded by the spatial distribution of epicenters. Figure 16 shows the strike of the east-dipping plane from each focal mechanism, mapped at the epicenter of that earthquake. Rather than being aligned along a single direction, the pattern of rupture planes is more like an en-echelon set.

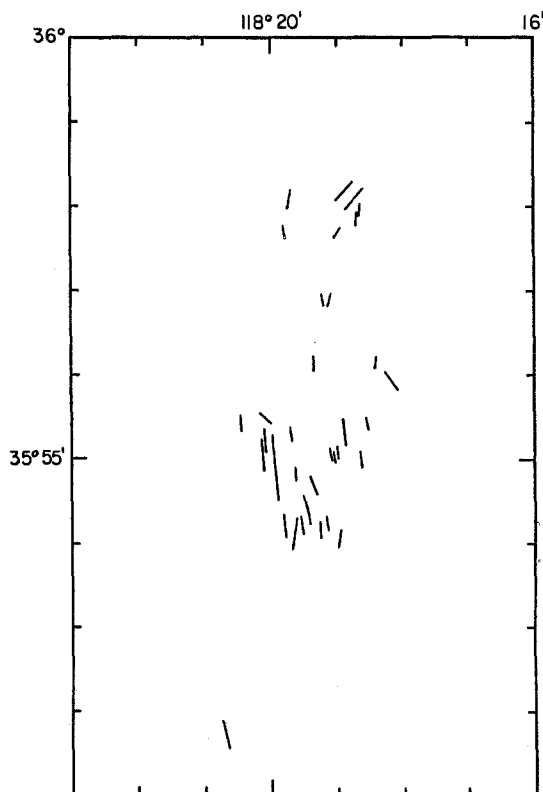


FIG. 16. Schematic map showing locations of  $M_L \geq 3.0$  earthquakes in the Durrwood Meadows swarm. Symbol for each earthquake is a line parallel to the strike of the east-dipping plane in the focal mechanism determined for that event. Length of this line is proportional to the magnitude of that earthquake, by the length-magnitude relation of Kanamori and Anderson (1975).

The consistency of the focal mechanisms and the en-echelon pattern of the rupture planes and epicenters (Figure 16) together imply that the Durrwood Meadows swarm did not occur along one fault. However, the southern Sierra Nevada seismic lineation along which the Durrwood Meadows swarm occurred had the highest level of microseismic activity in southern California during 1984. As many  $M_C \geq 2.0$  earthquakes occurred in this belt as on the San Jacinto fault, generally the most active fault in southern California (Figure 2). One explanation of this discrepancy is that a zone of weakness is now forming within the Sierra Nevada which may develop into a throughgoing fault in the future.

Other workers have proposed that the extensional tectonics of the Basin and Range Province is moving into the Sierra Nevada. Lockwood and Moore (1979)

documented microfault structures within the central Sierra Nevada that were compatible with basin-and-range tectonics. The Long Valley Caldera, 150 km north of Durrwood, is often cited as evidence of basin-and-range tectonics in the Sierra Nevada (e.g., Lachenbruch, 1979; Hill *et al.*, 1984; Bailey, 1984). Best and Hamblin (1978) suggested that the expansion of the Basin and Range into the Colorado Plateau along its east border should (because of the documented symmetry of the Basin and Range) be mirrored by similar expansion into the Sierra Nevada north of latitude 36°N. In addition, a few recent heat flow measurements in the southeastern Sierra Nevada (southeast of Durrwood Meadows and west of the frontal fault) indicate heat flow rates that are more compatible with a Basin and Range site than a Sierran site (A. H. Lachenbruch, personal communication, 1984).

The stress field inferred from the earthquakes in the Durrwood Meadows swarm is also compatible with basin-and-range tectonics. Although the overall extension of the Basin and Range is northwest-southeast, many localities within the province, including the area east of Durrwood Meadows, show east-west extension (Zoback and Zoback, 1980). The southern Sierra Nevada seismic lineation, along which the Durrwood Meadows swarm occurred, does, indeed, parallel normal faults in the adjacent area of the Basin and Range. Moreover, this seismic lineation is approximately 30 km west of the Sierran frontal-fault system, which is the average spacing between parallel faults in the Basin and Range (Wallace, 1984) and thus consistent with Basin and Range faulting geometry.

Therefore, this model proposes that the southern Sierra Nevada seismic lineation along which the Durrwood Meadows swarm occurred results from a basin-and-range normal fault beginning to form in the southern Sierra Nevada. Because a through-going structure is not yet developed, the primary mode of seismic deformation within the lineation is swarms. As the fault becomes more nearly continuous, however, larger earthquakes could occur along it.

#### DISCUSSION

The most important question raised by the 100-km-long seismic lineation in the southern Sierra Nevada is how it affects our estimation of the seismic hazard for the region. Several workers (e.g., Ryall *et al.* 1966; Wallace, 1978, 1984) have noticed a strong northerly lineation in the rupture zones of large earthquakes in the western Basin and Range Province. They have proposed that this zone, the central Nevada and eastern California seismic belt, is a continuous feature controlled by asthenospheric deformation and that sections of it which have not had large earthquakes recently could be considered seismic gaps (Wallace, 1978). Ryall *et al.* (1966) first proposed that this lineation (whose southernmost Basin and Range earthquake was the 1872 Owens Valley event) could be extended through the Sierra Nevada to include the 1952 Kern County earthquake and, beyond that, to Ventura on the California coast. Wallace (1978) suggested that this belt should not cross the San Andreas fault and proposed an end to the belt at the 1952 rupture. He defined the section between the 1872 and 1952 ruptures (within which the present Durrwood Meadows swarm is located) as the southern Sierra seismic gap and the possible site of an  $M = 7+$  earthquake. He later (1984) suggested that the 1952 rupture was not part of this seismic belt because it was a thrusting event, whereas all of the others showed normal faulting. He proposed that the southern Sierra seismic gap should lie along the east side of the Sierra Nevada.

The pattern of  $M \geq 7.0$  earthquakes along a north-northeastward trend through the western Basin and Range makes a large earthquake near the southern Sierra

Nevada plausible; the question is whether this earthquake would occur within the Sierran block or east of it (Wallace, 1978, 1984). Two previous arguments against a large earthquake within the Sierra Nevada were that earthquake mechanisms do not show normal faulting and that no fault capable of an  $M = 7+$  event exists west of the frontal fault. Both arguments are weakened, however, by the evidence from the Durrwood Meadows swarm. As discussed above, the mechanisms at Durrwood Meadows are consistent with basin-and-range extension. In addition, a 100-km-long seismic lineation is apparent within the Sierra Nevada, comparable in length to the rupture zones of  $M \geq 7.0$  earthquakes within the western Basin and Range.

The primary argument against the possibility of an  $M \geq 7.0$  earthquake within the Sierra Nevada is that the seismic lineation within the Sierra, although the site of numerous small and moderate events, may not be continuous enough to accommodate such a large earthquake. Many seismically active regions have been shown to have either swarms or large earthquakes, but not both. For example, the central San Andreas fault (Allen, 1981), mid-oceanic ridges (Sykes, 1967), and the Brawley seismic zone (Johnson and Hill, 1982) are all characterized by swarm activity and few large earthquakes. In some places, swarms and large earthquakes occur together, especially at sites of intracontinental deformation, such as in Soviet Central Asia (Kristy and Simpson, 1980) and western China (Jones *et al.*, 1984). However, the causative faults of the large earthquakes at both of those sites were geologically evident.

The absence of a continuous fault and the predominance of swarms within the southern Sierra Nevada seismic lineation seems to make an  $M \geq 7.0$  event unlikely, but not necessarily impossible. A much longer period of deformation may be needed to develop a fault capable of generating such a large earthquake. However, the Walker Pass area, only 30 km east of Durrwood Meadows, has been the site of an  $M_L = 6.3$  and several  $M_L \geq 5.0$  earthquakes within the past 40 yr without a geologically obvious fault. The southern Sierra Nevada seismic lineation could also be the site of an earthquake one to two units of magnitude larger than those recorded in 1983 through 1984.

The possible relation of the Durrwood Meadows swarm to magmatic activity must be considered because of the common relation of earthquake swarms to movements of magma (e.g., Sykes, 1967). Magma chambers have been recognized near the Durrwood Meadows area (such as the Coso geothermal field and Long Valley caldera), and the extensional phase of basin-and-range tectonics is commonly characterized by volcanism (Best and Hamblin, 1978). Indeed, Okaya and Thompson (1985) have suggested volcanic intrusions as a primary mechanism for the formation of basin-and-range normal faults. The Golden Trout Creek volcanic center, an unglaciated basalt that is presumably no more than 10,000 yr old, lies along this lineation at its north end (Moore and Lamphere, 1983).

However, nothing but the common association of swarms with volcanoes suggests magmatic activity at Durrwood Meadows. The  $b$  value of the swarm is 0.9 to 1.0, approximately the same as the average  $b$  value in southern California (Hileman, 1978) and not the high value recorded for some volcanic swarms (e.g., Einarsson and Brandsdottir, 1980; McNutt and Beavan, 1984). The earthquake activity associated with magma movement at Long Valley caldera occurs over a much larger depth range (Savage and Cockerham, 1984) than the Durrwood Meadows swarm and does not show the same linear distribution, over a length of 100 km, as in the southern Sierra Nevada. In addition, the orientations of focal mechanisms range more widely during swarms in Long Valley than at Durrwood Meadows (Savage

and Cockerham, 1984). More heat flow data and geodetic measurements will be needed to help resolve this question.

### CONCLUSIONS

The Durrwood Meadows swarm that occurred in the southern Sierra Nevada starting in October 1983 is characterized by a complex pattern of epicentral distributions and a simple set of focal mechanisms. During the first 17 days of the swarm, epicenters were distributed along a northwestward trend. Later bursts of earthquakes were distributed along northeastward and other, northwestward trends offset to the north from the original distribution. The  $M_L \geq 3.0$  earthquakes that occurred within these trends all had focal mechanisms consistent with almost pure normal faulting along a north-south-striking plane. The consistency of these focal mechanisms with each other, and the en-echelon pattern formed by the rupture planes and earthquake epicenters, imply a homogenous stress field and the absence of a large fault structure.

In spite of this implied absence of a large fault in the area, the Durrwood Meadows swarm was part of a north-south-striking band of earthquakes that had one of the highest levels of microearthquake activity in southern California in 1984. This southern Sierra Nevada seismic lineation is explainable as the beginning of a basin-and-range fault in the Sierra Nevada. The lineation could be the site of an earthquake one to two units larger than those recorded in 1983.

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